Combined Pile Foundation System for a Residential Complex

Alvin K.M. Lam, *Geotechnical Engineer, Ove Arup & Partners Hong Kong Limited, Hong Kong, China; email: alvin.lam@arup.com*
Daman D.M. Lee, *Civil Engineer, Ove Arup & Partners Hong Kong Limited, Hong Kong, China; email: daman.lee@arup.com*

ABSTRACT: *For a high-rise residential complex in an urban area of Hong Kong, a large diameter bored pile foundation with steel stanchions was proposed to facilitate a top-down construction of a 3-level basement while allowing a concurrent construction of the superstructure. The final column load in some locations was too large to be supported by a single mega sized bored pile and hence supplementary bored piles were required to be built adjacent to the central bored pile with a connection via the pile cap to share the final structural loads. However, the capacities of these supplementary piles would not be fully utilized since the central bored pile directly supporting the column had been loaded prior to the connection via the pile cap. In lieu of the above, a collaborative effort among the designers and the Contractor was made to devise a combined foundation system using pre-bored H-piles to replace the supplementary bored piles. The innovative aspect was to apply pre-loading at the pile heads of the pre-bored H-piles using synchronized jacks upon reaching the pile head level with consideration of compatibility of pile head displacement in order to achieve full utilization of the capacities of both the central bored pile and the supplementary pre-bored H-piles under the permanent loading condition. This combined foundation system with pre-loading at the head of pre-bored H-pile resulted in substantial reduction in volume of pile excavation, lower construction risk, higher degree of flexibility in the construction programme, as well as lower construction cost.*

KEYWORDS: large diameter bored pile, rock socketted H-pile, pre-load, top-down

SITE LOCATION: IJGCH-database.kmz (requires Google Earth)

INTRODUCTION

The site is located at San Po Kong, Hong Kong covering an area of approximately 80 m by 120 m. The development consisted of five 37 to 41 storeys residential towers with a 3-level basement and a 5-level retail podium. The depth of the basement was about 13 m below existing ground.

The ground investigation revealed that the site comprises fill overlying a layer of marine deposit and alluvium. Underlying the alluvium is a thick layer of completely to highly decomposed granite. Bedrock consisting of moderately to slightly decomposed granite is encountered at depth varying from 40 m to 80 m below existing ground. The thickness of surficial deposits generally varies from about 7m to 12m. A corestone layer comprising moderately to highly decomposed granite with variable thickness is encountered immediately above the bedrock. Figure 1 illustrates the geological conditions at the site.

CONFORMING FOUNDATION DESIGN

In view of the site geology and the height of the towers, a large diameter bored pile foundation bearing on granitic bedrock with bell-out was proposed to be the foundation system. Top-down construction method was used to expedite the construction programme of the project such that the basement, podium and tower structures were constructed simultaneously. Diaphragm wall panels supported by permanent basement slabs were used as the retaining wall system for the top-down construction. The wall panels supporting the perimeter podium columns were founded on granitic bedrock with allowable bearing capacity of 5,000 kPa while other panels supporting the basement slabs only were founded on decomposed soil with standard penetration test of blow count values exceeding 200 and an allowable bearing capacity of

Submitted: 15 May 2013; Published: 19 August 2013
Reference: Lam, A.K.M, and Lee D.M.D. (2013). *Combined Pile Foundation System for a Residential Complex* International Journal of Geoengineering Case histories, http://casehistories.geoengineer.org, Vol.3, Issue1, p.1-9. doi: 10.4417/IJGCH-03-01-01

1,000 kPa. Inside the basement, steel stanchions protruding from the bored pile cut-off level to the ground level were constructed to support the temporary load from the basement, podium and tower structures at each column before the basement excavation and the pile cap construction were completed. However, due to the significant permanent column loads from the towers, the full capacity of a conventional 3 m diameter bored pile with bell-out was insufficient to sustain the loads at some columns and hence additional piles were required to be connected to these columns with the use of pile caps to share the loads upon reaching the final excavation level.

The foundation design adopted 81 large diameter bored piles with shaft diameters of 2.5 m and 3.0 m and bell-out diameter up to 4.5 m under each permanent column/stanchion to facilitate the top-down construction of the basement. Due to the significant column loads, another 55 large diameter supplementary bored piles were required to share the loads with the central bored pile via the pile cap upon reaching the final excavation level.

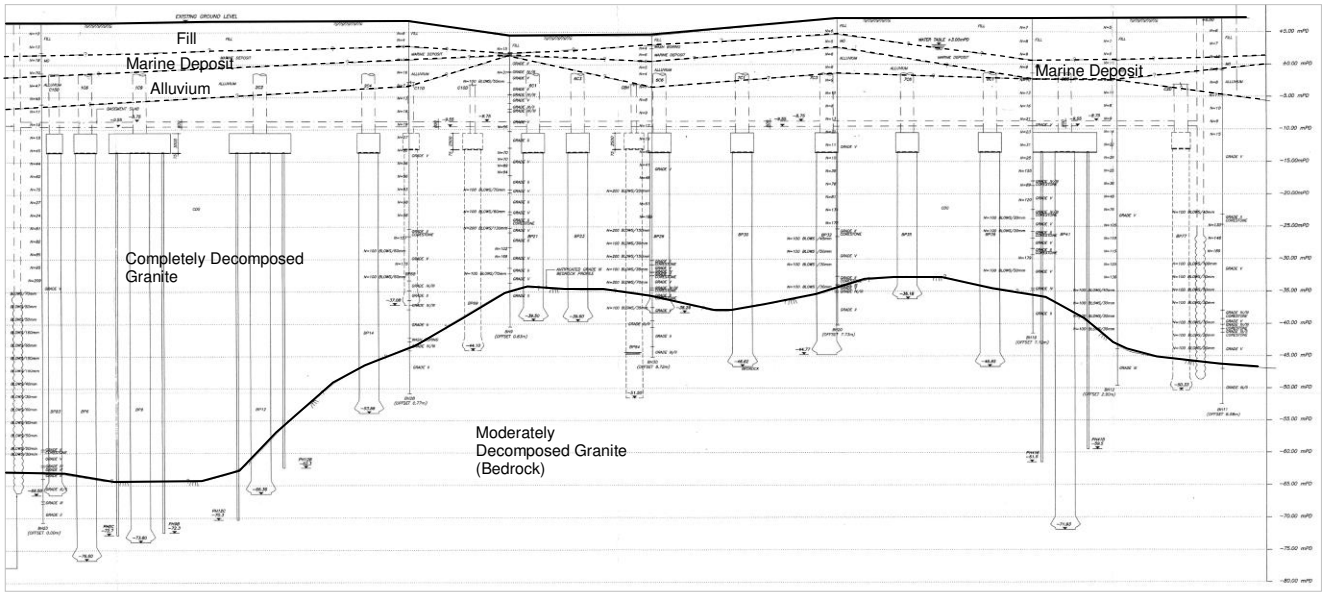

Figure 1. Geological profile of the site.

INNOVATION OF FOUNDATION DESIGN

The basement excavation and foundation works were tendered out in the form of a Design and Build contract, which provided tenderers with flexibilities to offer competitive alternative designs. The authors were engaged by one of the Contractors to derive an alternative foundation design. For the basement excavation, the Contractor basically adopted the conforming diaphragm wall design. In the foundation design, it was noted that the utilization of the capacity of the supplementary bored piles after connection with the central bored pile at the final excavation level was very low. This was because the central piles directly supporting the columns would have taken up all the temporary loads from the basement, podium and tower structures prior to the connection with the supplementary piles. After the connection, the remaining structural loads would then be evenly shared among the piles within the group and by default, the central pile in each group would first be loaded to its working capacity due to its lock-in stress before the connection. Inevitably, this design would result in significant wastages as the capacity of the supplementary piles would not be effectively utilised.

In the alternative foundation design, at each heavily loaded column, a large diameter bored pile with a bell-out diameter of up to 4.5 m and with an increased rock socket length up to 6 m was adopted to give a higher bored pile capacity directly underneath the column/steel stanchion as the central pile. The supplementary bored piles were proposed to be replaced by a total of 73 Grade 55C 305 x 305 x 223 kg/m (i.e. f_y = 460 MPa) pre-bored steel H-piles socketed into rock resulting in a combined foundation system supporting each column. The major part of innovation in respect to the foundation system is the introduction of pre-loading to the heads of these rock socketed H-piles upon casting the common pile cap. Through the process of pre-loading, the capacity of the two foundation systems could be fully utilized. With this alternative foundation design, there were substantial savings on concrete of approximately 9,500 m^3 and a reduction of excavated spoil in the order of about 9,000 m^3. The amount of steel used in the pre-bored H-pile was generally compensated by the amount of steel reinforcement needed for the supplementary bored piles. Also, the Contractor had the flexibility to mobilize different

piling equipment for the pre-bored H-pile installation and construct concurrently with the bored piles on site, which could shorten the overall construction programme. All these had contributed to significant savings on construction cost and time. The major risk to the Contractor, at the time of tender, was to obtain approval from the local authority as the jacking process was not previously introduced for foundation design in Hong Kong. A back-up scheme was therefore considered to use pre-bored steel H-piles without pre-loading. The number of pre-bored H-piles would be increased to 175. Though the amount of pre-bored H-piles was substantially increased, there was still considerable amount of cost saving to replace the supplementary bored piles by the pre-bored H-piles.

The Combined Foundation System

The large diameter bored pile was located at the column center to sustain both the temporary and permanent column loads while the supplementary pre-bored H-piles were located concentrically from the center of the pile cap at equal distance to share the permanent column loads. A typical pile layout is shown in Fig. 2. Once the piles are connected via a rigid pile cap at the final excavation level, the additional load will be shared between the central bored pile and the supplementary pre-bored H-piles based on their corresponding axial stiffnesses. However, the capacity of these supplementary piles could not be fully utilized as the bored pile directly supporting the columns has been stressed up during the course of top-down construction prior to such connection. In order to counter this out of step sequence of loading to the central and surrounding piles, a process of pre-loading is carried out at the head of pre-bored H-piles to release this lock-in stress in the bored pile such that additional loads shared between bored pile and pre-bored H-piles can subsequently fully utilize the capacity of these piles.

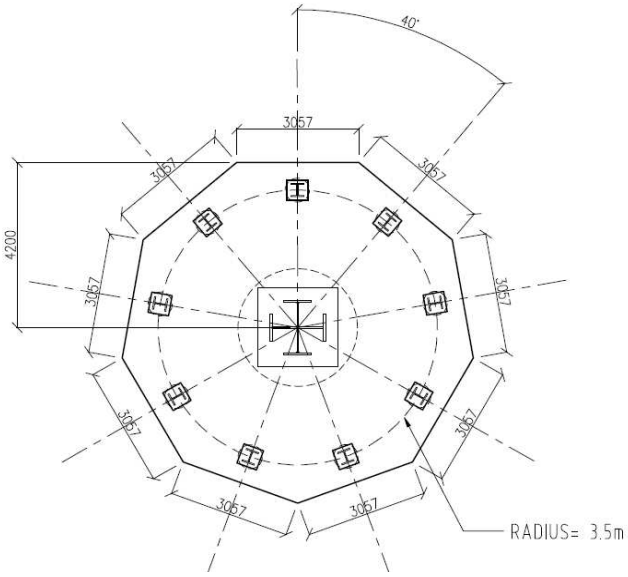

Figure 2. Typical pile layout with 9 supplementary socketed H-pile.

The pre-loading was proposed to be carried out at the head of pre-bored H-piles using pressurized jacks. Two jacking systems were considered, namely flat jack and hydraulic jack. Flat jack was designed to be situated at the head of pre-bored H-pile and was part of the permanent structural element. After the required pre-loading force was achieved, the jack oil inside the flat jack would be displaced and filled up by epoxy resin and the injection pressure would be monitored by the pressure gauge during the displacement process. However, as the flat jack was not designed for shear load transfer, additional stiffening elements were required. A typical pile head detail using a flat jack is shown in Fig. 3.

An alternative to a flat jack was two hydraulic jacks, which were eventually used in this project. The advantage of using two hydraulic jacks over a flat jack was that they were only for temporary use and the axial pile load would be permanently transferred through the shim plates, which were made of structural steel. The shim plates, when properly welded, could also faciliate the transfer of shear load from the pile cap to the pre-bored H-pile. Instead of a single hydraulic jack placed concentrically along each pile, two hydraulic jacks were proposed to place on either side of the pre-bored H-pile. This is to faciliate the installation of shim plates directly above the head of the pre-bored H-pile for direct load transfer from the pile

cap to the pile. In order to support the hydraulic jacks, two brackets on either side of the head of the pre-bored H-pile were constructed and a hydraulic jack was placed on top of each bracket. When the required pre-loading force was achieved, the shim plates would be installed and welded at the head of the pre-bored H-pile to lock the jack force. These shim plates would form part of the permanent pile element. The hydraulic jacks would then be unloaded and removed.

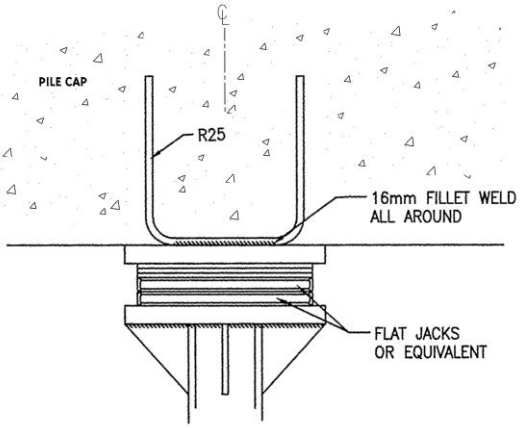

Figure 3. Typical pile head detail using flat jack.

Synchronized jacks were used to apply the same load to each pre-bored H-pile. With the concentric arrangement of the pre-bored H-pile, no differential stress would be induced to the head of the bored pile. Prior to locking the jack force via the insertion of shim plates, the rate of pile head settlement would need to be controlled to less than 0.05 mm in 10 minutes to each of the pre-bored H-pile. A typical pile head detail using two hydraulic jacks is shown in Fig. 4.

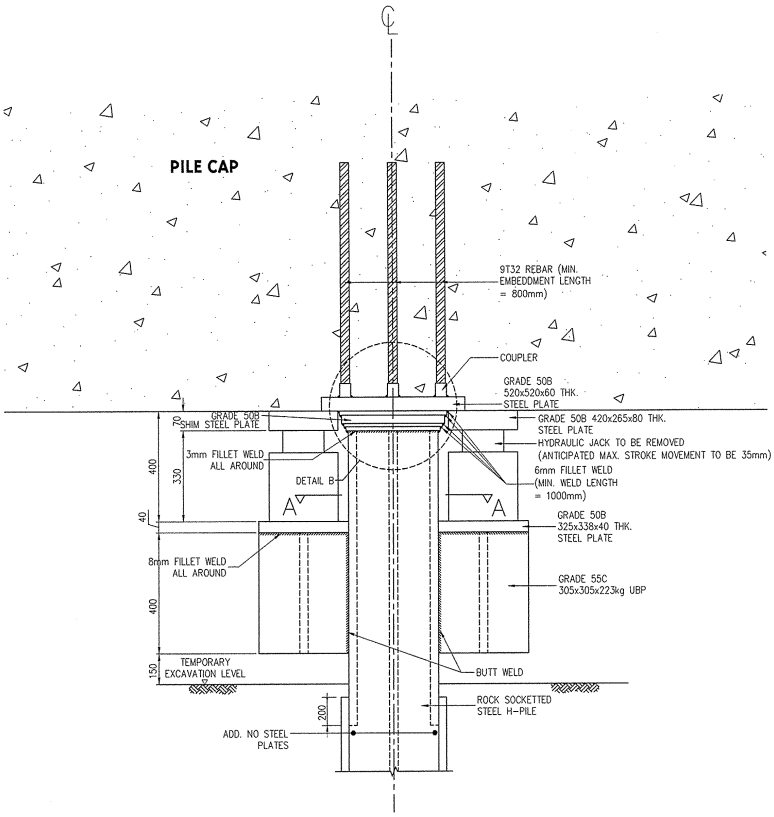

Figure 4. Typical pile head detail using hydraulic jack.

Pile Design Capacities

The bored pile and pre-bored H-pile were designed in accordance with the Code of Practice for Foundations (BD, 2004). The rock socket friction for both bored pile and pre-bored H-pile in rock was taken to be 700 kPa under compression and transient wind load while the end bearing capacity for bored pile bearing on rock was taken to be 5,000 kPa.

A 3 m diameter bored pile (i.e., 2.85 m diameter within the rock socket) with a bell-out diameter of 4.5 m and rock socket length of 6 m provided an allowable working capacity of 117 MN. Concrete with cube strength of 45 MPa was adopted and a tremie factor of 0.8 on concrete strength was allowed in the design considering that the concrete was placed underwater. Compression steel reinforcement was required due to the high axial stress.

The pre-bored H-pile derives its capacity by rock socket friction. For a 610 mm diameter pre-bored H-pile (i.e. 550 mm diameter in rock) with a steel section of 305 x 305 x 223 kg/m Universal Bearing Pile (UBP), the allowable working capacity with 6.5 m rock socket length was 5.9 MN. In order to offset the additional axial and bending stresses due to lateral load effects and construction tolerances, the typical capacity of the pre-bored H-pile would be 5.6 MN. With a maximum of 9 supplementary pre-bored H-piles at each column, the maximum combined allowable axial capacity is up to 167 MN upon full mobilization.

Optimized Jack Force

Prior to the construction of the pile cap, the temporary vertical loading including dead, live and wind loads are transferred directly onto the bored pile, denoted by F_1. Assuming that the jack force on the pre-bored H-pile is denoted by P, the load on bored pile after jacking is $F_1 - NP$, where N is the number of pre-bored H-piles within the pile cap . After the bored pile and pre-bored H-piles are connected via a rigid pile cap, the additional load, denoted by F_2, will be shared among them depending on their corresponding stiffnesses. The loads on bored pile and pre-bored H-piles in permanent condition are formulated in equations (1) and (2) respectively. The interaction among the piles in the group is ignored.

$$F_1 - NP + \frac{F_2 k_B}{k_B + N k_H} \tag{1}$$

$$P + \frac{F_2 k_H}{k_B + N k_H} \tag{2}$$

where F_1 = dead, live and wind loads before jacking, F_2 = additional dead, live and wind loads after jacking, P = jack force on each pre-bored H-pile, k_B = vertical stiffness of bored pile, k_H = vertical stiffness of pre-bored H-pile and N = number of pre-bored H-piles within the pile cap.

An optimized jack force to fully utilize the capacity of both bored pile and pre-bored H-pile can be determined by considering the pile head movement at different stages of loading. The pile head settlement required to mobilize the full capacity for both bored pile and pre-bored H-pile are represented by equations (3) and (4) respectively. Prior to connection via the pile cap, the pile head settlement of the bored pile can be determined by equation (5). When the jack force P is applied to the head of pre-bored H-pile, the head of bored pile moves upwards while that of pre-bored H-pile moves downwards. The magnitudes of pile head movement for bored pile and pre-bored H-pile due to jacking are represented by equations (6) and (7) respectively.

$$\Delta_B = \frac{P_B}{k_B} \tag{3}$$

$$\Delta_H = \frac{P_H}{k_H} \tag{4}$$

$$T_B = \frac{F_1}{k_B} \quad (5)$$

$$S_B = \frac{NP}{k_B} \quad (6)$$

$$S_H = \frac{P}{k_H} \quad (7)$$

where Δ_B = bored pile settlement at full load, Δ_H = pre-bored H-pile settlement at full load, T_B = bored pile settlement at temporary load, S_B = bored pile upward movement due to jacking force, S_H = pre-bored H-pile downward movement due to jacking force, P_B = bored pile allowable capacity and P_H = pre-bored H-pile allowable capacity.

After jacking, the remaining movement before the full capacity of bored pile is reached can be calculated by (3) + (6) – (5) while that of pre-bored H-pile can be calculated by (4) – (7), which can be represented by equation (8), as both bored pile and pre-bored H-pile shall move together after connection via the cap to achieve full utilization of the allowable pile capacities. The optimized jack force can then be determined by rearranging equation (8) to obtain equation (9).

$$\Delta_H - S_H = \Delta_B + S_B - T_B \quad (8)$$

$$P = \frac{\Delta_H - \Delta_B + T_B}{\left(\frac{N}{k_B} + \frac{1}{k_H}\right)} \quad (9)$$

In determining the optimized jack force, the allowable working capacities of bored pile and pre-bored H-pile were considered. Under ultimate load condition, because of the relatively higher stiffness of the bored pile, it would share more column loads than the pre-bored H-pile. The bored piles were therefore designed to sustain this extra load under the ultimate condition. The vertical stiffness values of both bored pile and pre-bored H-pile were estimated based on the assumption of elastic behavior of the piles. Considering that the capacities of the piles are solely derived from the rock socket friction and/or end bearing, the contribution from the soil friction was not taken into account in estimating the stiffness values. This assumption was found to be appropriate given the pile load, pile size, pile arrangement and geological conditions at the site.

Mechanism of Pre-loading

Figure 5 illustrates the mechanism of pre-loading for the supplementary pre-bored H-piles. The column with the greatest loading of 167 MN supported by one large bored pile and nine supplementary pre-bored H-piles is selected. The loading sequence is generally divided into three stages. “Stage 1” refers to the temporary column load solely taken by the central bored pile via the steel stanchion prior to the connection with the pre-bored H-piles. “Stage 2” refers to the preload applying to the head of each pre-bored H-pile and locked by shim plates. “Stage 3” refers to the sharing of remaining column load within the combined foundation system. Prior to the commencement of excavation, the central bored pile and the pre-bored H-piles are constructed at existing ground level with pile cut-off at the soffit of basement. Steel stanchion embedded inside the bored pile is used to facilitate the transfer of temporary column load during the course of top-down construction. When excavation to final formation level is reached and prior to conducting pile jacking, the dead weight of the pile cap, the podium structure, the basement floors except the base slab and the residential towers to 8 storeys are supported by the central bored pile, which is estimated to be 62 MN in Stage 1. In Stage 2, pile jacking is conducted with optimized jack force of 3 MN for each pre-bored H-pile, which helps to release the load on the central bored pile by 27 MN. Once the jack force is locked into the pre-bored H-pile by shim plates in Stage 2, these piles will share the remaining column load of 105 MN with respect to their corresponding axial stiffness in Stage 3 (i.e., additional 82 MN on central bored pile and 2.6 MN on each pre-bored H-pile). As such, the central bored pile and each pre-bored H-pile will share 117 MN and 5.6 MN respectively under working condition.

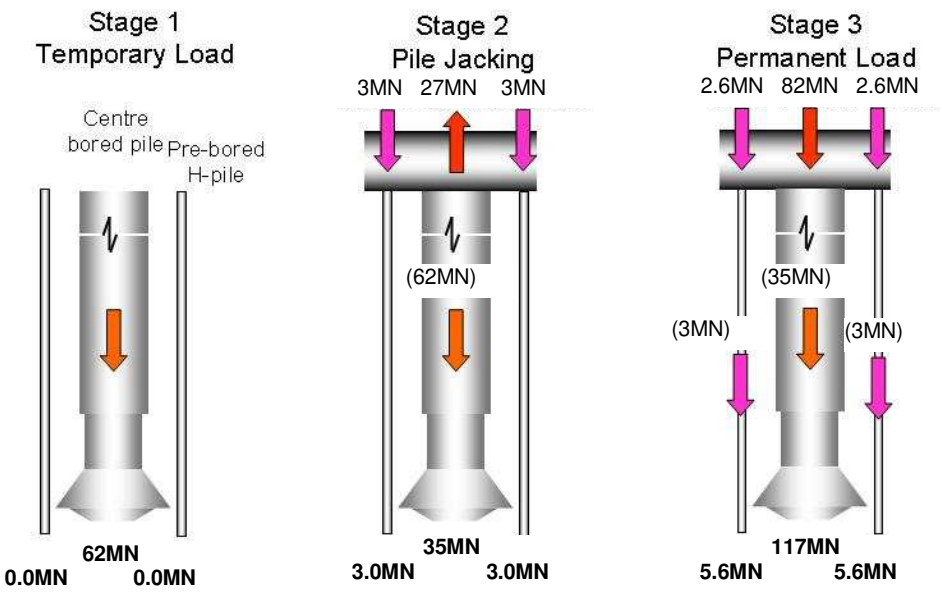

Figure 5. Illustration of load transfer with pile jacking.

PILE CONSTRUCTION

Large Diameter Bored Pile

The bored piles were installed with a conventional piling technique in Hong Kong using a full length temporary steel casing to support the pile bore through the soils. A hammer grab was used to excavate through the superficial deposits and decomposed materials. The temporary steel casing with cutting teeth at the toe was advanced simultaneously by an oscillator or a rotator as the excavation proceeded. During pitching, the verticality of the temporary casing was checked by a spirit level periodically and the casing was lengthened by casing joint or welding until hard stratum or bedrock was reached.

The rock socket was then formed by a reverse circulation drill (RCD) and the rig was securely located on the top of the casing as shown in Fig. 6. The drilling action was provided using a straight-sided drill bit and the cuttings were airlifted out of the pile shaft with water. The bell-out was formed by using an expandable drill bit mounted onto a RCD rig to form the designated dimension. When the founding level was reached, the pile base was cleaned by using the airlifting method followed by the installation of prefabricated steel reinforcement cages and tremie concreting. During the course of concreting, the temporary steel casing was gradually withdrawn.

Pre-bored H-pile

The pre-bored H-piles were constructed using an ODEX drill bit in soil followed by a down-the-hole (DTH) hammer to form the rock socket. A hole of 610 mm diameter was drilled into the ground and a temporary steel casing was advanced simultaneously with the ODEX drill bit to support the soil. The casing was lengthened by full penetration butt-welding and installed into bedrock. A rock socket with 550 mm diameter was then formed by a DTH hammer to the required level. The steel H-pile section was then lowered into the hole in the specified orientation and the void was filled up by tremie cement grout followed by the withdrawal of the temporary casing. At each pile cap, one steel H-pile section was extended to existing ground level to facilitate the performance of proof load test to 2 times of the allowable capacity of the pile. Figure 7 illustrates the drilling rig for the construction of pre-bored H-piles.

Figure 6. RCD mounted on casing top.

Figure 7. Pre-bored H-pile construction.

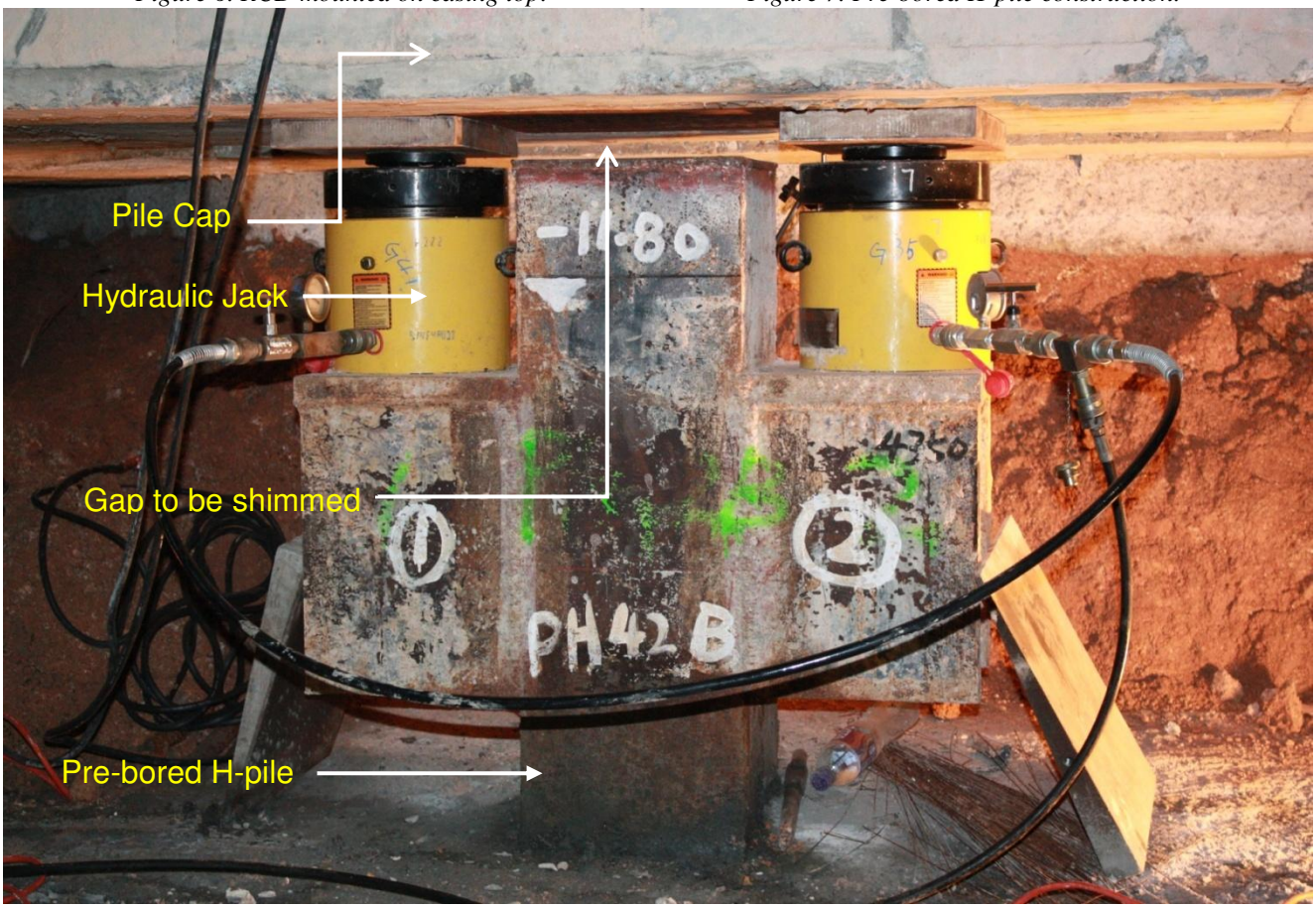

Figure 8. General view of head of pre-bored H-pile underneath the pile cap during the pre-loading process.

PRE-LOADING PROCESS

When the basement excavation was carried out to the final formation level, the capping plates at the head of pre-bored H-pile were installed and the steel plates embedded into the pile cap were positioned and leveled against the capping plate of the steel H-pile. Once the pile cap had attained the required strength, local excavation was carried out around the head of the pre-bored H-pile to facilitate the installation of steel brackets supporting the hydraulic jacks. The hydraulic jacks were synchronized via a single jacking unit in order to attain the same jack force for each pre-bored H-pile during the jacking process. When the design jack force was reached, two shim plates were inserted at the gap between the capping plate of the steel H-pile and the steel plate embedded into the pile cap. Where necessary, additional steel plates would be inserted to accommodate the width of the gap. These shim plates together with the additional plates were joined together by fillet welds in order to lock the jack force in the pre-bored H-pile. The hydraulic jacks were subsequently unloaded and removed. Figure 8 illustrates the pre-loading process prior to the shim plate installation.

CONCLUSIONS

The combined foundation system, using the large diameter bored piles as the central pile and pre-bored H-piles located concentrically from the central piles, provides a cost effective and sustainable foundation solution to support mega column loads under a top-down construction sequence. The innovation of applying pre-loading, via a synchronized jacking system to the supplementary pre-bored H-pile, enables the capacity of both the bored pile and pre-bored H-piles to be fully utilized. The pre-loading process is introduced to foundation design for the first time in Hong Kong and is successfully implemented with satisfactory pile group settlement performance. With a total of 9 supplementary pre-bored H-piles to supplement the loading of the central bored pile, the combined allowable axial capacity can be as high as 167 MN.

The design and build contract provides flexibilities to the Contractor to offer the most cost effective foundation design to support mega column loads in this project. The initiatives and collaborative efforts among the designers and the Contractor to derive and implement an innovative foundation design are the key successes of this project. The risk to the Contractor at the time of tender had to be properly assessed and suitable fall back scheme is vitally important in limiting the contractual risks to all parties.

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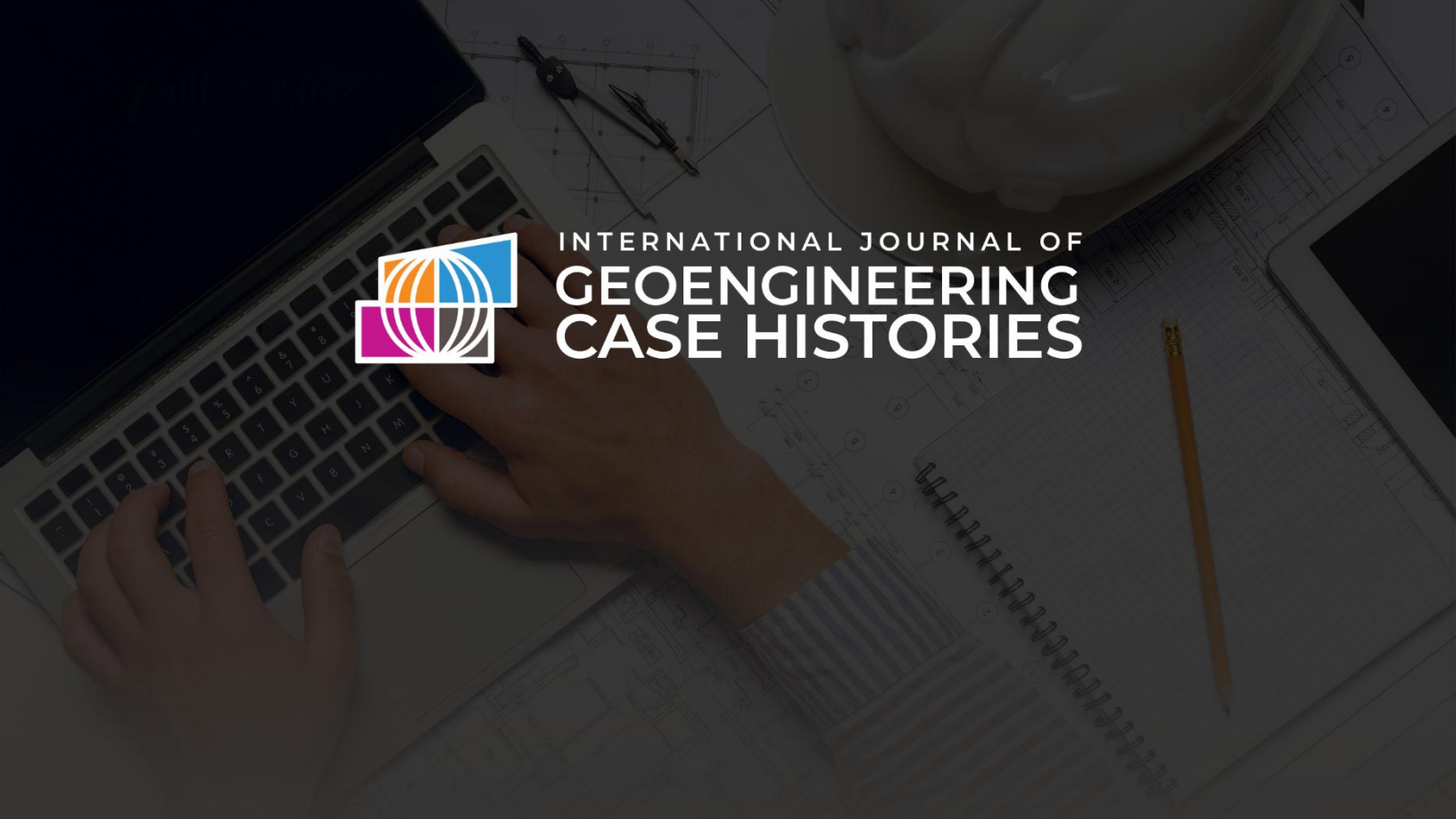

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